THE COMPRESSIVE STRENGTH OF LIGNOSULPHONATE STABILISED EXTRUDED EARTH MASONRY UNITS

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Abstract
Earthen (unfired clay) bricks offer several distinct advantages over conventional fired clay bricks and other high energy masonry units. Most notably there is significantly lower environmental impact, including carbon emissions during manufacture, than comparable products, with unfired clay bricks having an estimated 14% of the energy of fired bricks and 25% of concrete blocks. Earth construction is able to provide passive environmental controls; including the regulation of temperature and humidity which can be utilized in unfired clay masonry to improve internal levels of comfort. The commercialisation of unfired clay masonry as a structural material is dependent on several factors. Modern earthen construction methods need to fit in with demands of contemporary construction, compete commercially and provide a high quality consistent performance. To ensure that thin walled unfired clay masonry can be used in a load bearing application, it is important to consider the effect high moisture content, due to accidental and intentional wetting, has on the strength of the material as well as the building unit. The proposed paper presents initial findings from an investigation into the development of low impact alternative stabilisers. Cement and lime are widely used in some countries, but both have an associated embodied energy and carbon emissions that may hinder the benefits of unfired clay as a mainstream building material. The use of lignosulphonate was chosen as a way of minimizing the adverse environmental impacts whilst improving water resilience, an essential requirement for thin walled loadbearing masonry using earth. Unconfined compressive strength of extruded soil samples that have been stabilized by three types of lignosulphonate. Specimens were tested both dry and wet as a basis for comparing loss of strength due to exposure to a wet environment.

1 INTRODUCTION

Within the UK, the heritage of earthen construction largely ended during the 19th century, which is attributed to the industrialisation of the construction industry (Morton, 2008, p.17). There has been a renewal of interest in earthen construction within the past 30 years due to the increasing interest in sustainable forms of construction (Walker, 2004, p.249).

For the beneficial effects of any sustainable form of construction to have a significant and widespread impact then factors in addition to the embodied energy and carbon should be considered. The form of construction should also be easily adopted into current construction practice with a minimum shift in the end use by society. In this regard, any sustainable construction should be comparable to current materials with respect to durability and maintenance.

The focus of this paper is on modern earth masonry that is commercially produced. This enables the benefits of earthen construction to be delivered to the mass market with improved quality control. Earthen bricks can be produced following the well established manufacturing procedure as commercially produced fired bricks but without the firing. This allows the commercially produced extruded earth units have about 14% of the embodied carbon of equivalent fired clay bricks (Morton, 2008, p.4). Based on typical figures in the Inventory of Carbon and Energy (Hammond and Jones, 2011), it can be shown that a 225mm thick unstabilised earth masonry wall has the similar embodied energy to a 100mm thick commercially produced dense concrete block. It is therefore environmentally and financially desirable to keep walls as thin as possible.

The compressive strength of extruded earth masonry measured at ambient temperature and humidity levels ranges from 2.8 to 5.1MPa (Heath et al., 2009, p110). Therefore there is scope for these units to be used within a 100mm thick loadbearing wall in a two storey domestic application.

Heath et al. (2009, p.108) developed and demonstrated the exponential relationship between compressive strength and water content for extruded unfired clay masonry units. With increasing moisture content the compressive strength of the units decreased. This reduction in compressive strength is critical for thin walled load bearing masonry. Accidental or intentional wetting would clearly create an elevated moisture content which would significantly reduce the strength of the material as well as the masonry that would ultimately lead to collapse.

Typically cement can be added to improve strength and reduce water susceptibility. Using the data in the Inventory of Carbon and Energy (Hammond and Jones 2011) it can be shown that a cement content of 5% in an earth block will increase the embodied energy to a level similar to dense concrete blocks, eliminating one of the environmental benefits.

There has been a growing interest in using alternative low embodied carbon stabilisers. Lignosulphonates are natural polymers derived from lignin that binds cellulose fibres together and is typically a by-product from the paper industry (Brandon et al., 2009, p.12). These materials are commonly used in commercial brick manufacture to provide sufficient “green” (wet) strength to prevent damage during handling.

The objectives of the work presented in this paper were to study, compare and report on the strength characteristics of extruded earth masonry. Following a review of the stabilisation mechanism of lignosulphonate, an experimental programme of compressive strength was completed using scaled extruded earth bricks made of the same brick clay with varying types of lignosulphonate.

2 STABILISATION MATERIALS AND METHODS FOR CONSTRUCTION

Stabilisation offers a method of improving the inherent properties of soil. Many of the traditional and non-traditional methods of were developed for the stabilisation of unpaved roads (Tingle and Santoni, 2003, p.72). Typically this has focused on improving the Unconfined Compressive Strength (UCS), Californian Bearing Ratio and erosion characteristics of the roads. The outcomes of the literature concerning the use of non-traditional stabilisers for road improvement can be transferred for the possible use in building structures.

Potential mechanisms by which stabilisation of the soil can occur have been summarised by Tingle and Santoni (2003, p.74) and include:

- Encapsulation of clay minerals
- Cation exchange
- Chemical breakdown of the clay
- Absorption of organic molecules into the clay interlayer

The non-traditional additives are either by-products of an un-related process or alternatively they have been developed specifically. Lignosulphonates are by-products that have a wide variety of uses including acting as a plasticiser for making concrete. Lignosulphonate ($C_{20}H_{26}O_{10}S_2$) is an anionic polyelectrolyte that form salts typically with sodium, calcium and ammonium cations.

Lignosulphonate stabilises soil by physically binding the soils particles together with minor chemical effects (Tingle et al., 2007, p.61-62). Individual soil particles can become coated in a thin adhesive-like film that acts to cement the particles together. Lignosulphonates are ionic and therefore there is potential for cation exchange that can alter the molecular structure of the soil. This has the potential to reduce the surface charge that can lead to flocculation, close packing and hydrophobic characteristics (Xiang et al., 2010, p.886).

Santoni et al. (2005, p.34-42) tested lignosulphonate on a compacted silty sand material. The addition of 3% lignosulphonate solution caused a 22% reduction in UCS compared to an un-stabilised sample at seven days. Lignosulphonate specimens were tested under the ‘wet’ conditions. In preparation specimens were placed for 15 minutes in an inch (25.4 mm) of water. When tested in this method, at seven days the lignosulphonate stabilised specimens showed, as expected, a decrease from the dry specimens’ UCS. When compared to the equivalent un-stabilised specimens tested using the ‘wet’ method, the lignosulphonate stabilised specimens were on average 620% stronger and gave a UCS of 1.1 MPa.

The effect of lignosulphonate on low plasticity soils resulted in a greater UCS (Tingle and Santoni, 2003, p.78). An optimum concentration of 1.5% powdered lignosulphonate resulted in a UCS of 7.3 MPa, while a UCS of 4.8 MPa was achieved under ‘wet’ testing conditions. Within the same test matrix performed by Tingle and Santoni (2003, p.78), lignosulphonate stabilisation achieved a 30% greater UCS than a 9% cement addition under dry conditions and a marginal increase in strength under ‘wet’ testing.

Although the literature has been limited, it has shown that there is potential for lignosulphonate to be used a soil stabiliser. The potential ion exchange mechanism warrant further research with varying types of lignosulphonate to investigate if there are any noticeable effects. The unique method of brick production by extrusion with the

benefits of stabilisation using byproducts may yield an unfired masonry unit suitable for a loadbearing application without the risk of potential mechanical wetting.

3 EXPERIMENTAL MATERIALS

All the experimental bricks were produced using the same brick clay. The soil is described as a brick clay as it is used for commercial fired brick production. The brick clay was chosen rather than blending materials, as this is the material that is currently used for production therefore any stabilisation method would be required to work with fundamentally the same material. The grading and Atterberg characteristics are outlined in Table 1. The soil can subsequently be described based on grading as a dark brown slightly sandy silt with the plasticity of a low plasticity clay. The clay mineralogy was identified by XRD as containing 39% kaolinite and 2% montmorillonite with significant amount of quartz and minimal amounts of other minerals.

For this study, sodium (Na), calcium (CA) and ammonium (Am) lignosulphonate were supplied in dry powder form. The clay was stabilised by adding 2.5% (by dry mass) of the dry powder lignosulphonate.

Table 1: Soil characteristics

Property	
Grading (by mass)	
Fine gravel fraction (2–6 mm) (%)	5
Sand fraction (0.06–2 mm) (%)	33
Silt fraction (0.002–0.06 mm) (%)	46
Clay fraction (<0.002 mm) (%)	16
Atterberg Limits	
Liquid Limit	24
Plasticity Index	8

4 EXPERIMENTAL PROGRAMME

The bricks were manufactured within a laboratory environment at The University of Bath. This was achieved using a vacuum pug mill extruder able to produce bricks at 1:3 linear scale, thus 1: 27 volumetric scale as shown in Fig. 1. This machine creates a similar production process as full scale extruded bricks. Clay that has been pre-mixed with the required water content is fed in to a series of augers that help to homogenise the mixture. Under a vacuum the clay is effectively compressed by reducing the cross sectional area at the point of extrusion to 72mm by 34mm. This produces a column of clay that is then cut into 22mm thick bricks.

Initial testing was undertaken to determine the optimum moisture content (OMC) for the extrusion of the bricks. This was achieved by adding varying amounts of water to the clay mixture and feeding it through the extruder and measuring the water content and dry density of the bricks that were produced. This was compared to the modified Proctor method of determining the OMC. Extruding at a moisture content less than the plasticity limit caused notable cracking in the brick surface, and extrusion was not possible at a moisture content less than 14%. The OMC for extrusion is therefore at the plasticity limit of 16%. It is clear from Fig. 2 that the modified proctor is unsuitable for determination of OMC for extrusion. The addition of the various lignosulphonate did not change the plasticity limit and therefore did not change the OMC for extrusion.

Fig. 1: Laboratory vacuum pug mill extruder

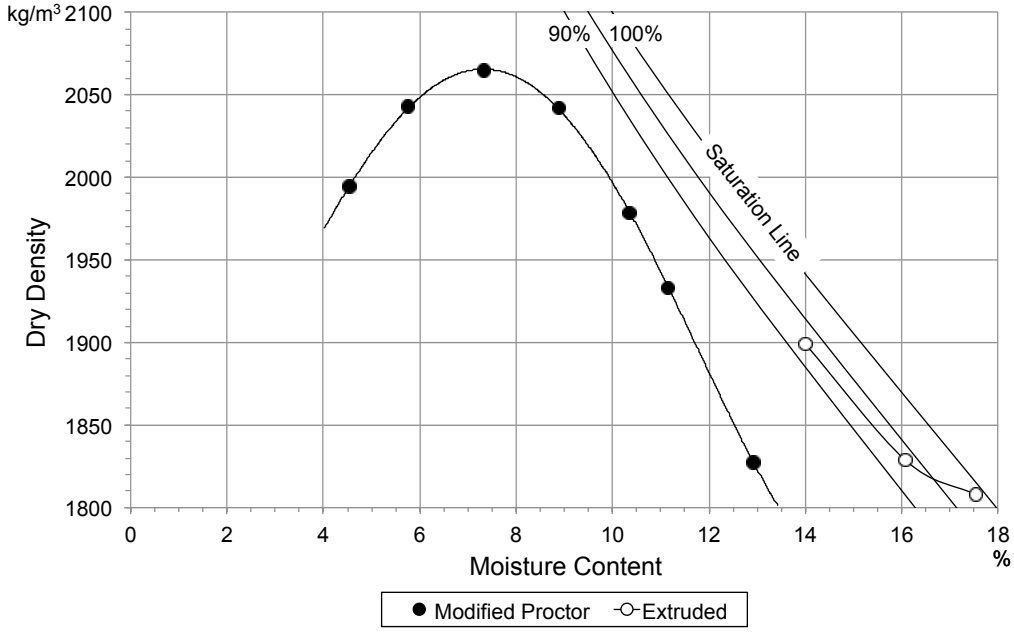

Fig. 2: OMC of clay soil

Each sample was prepared by first dry mixing 2.5% of the powder lignosulphonate into the brick clay. Water was then added to achieve a mixture with moisture content of 16%. This mixture was then transferred and fed through the extruder under a vacuum of 0.5 bar. The extruded column of clay was cut to form the bricks of dimensions 72 x 34 x 22mm and the bricks were immediately weighed with additional samples of extruded clay were taken for moisture content measurements.

The drying regime, curing time and testing condition were varied to independently assess the effect on stabilisation mechanism. The drying procedure was varied to investigate if any stabilisation effect would be facilitated or accelerated by variation in the drying regime. All of the bricks were dried within the laboratory for two days, following that the drying procedure varied. Random samples of bricks were continued to be dried in the laboratory environment (average of 21.5°C at 61% relative humidity) while the drying of other bricks was accelerated. One sample of bricks were artificially dried in an oven at 60°C with another were dried at 105°C. Following two days within the ovens they were then removed and stored within the laboratory until testing. To investigate the development of strength, bricks were first tested at 14 and 28 days. Finally testing occurred on dry and wet samples. The wet testing regime involved fully immersing the bricks in distilled water for 24 hours prior to testing. This meant that in total 12 different test methods were considered.

Block dimensions, dry density, uniaxial compressive strength were determined using a representative sample of six specimens for each of the 12 tests. Brick compressive strengths were measured by crushing specimens in their normal aspect without any capping. The load was measured with an applied constant displacement rate of 2.5mm/min. The results were averaged for each testing method and the methodology repeated for each different stabiliser. Each brick was compressed until peak load was reached.

5 RESULTS

The results of the compression test on the stabilised sample as well as an unstabilised sample for control is provided in Table 2, Figs. 3 and 4. The control sample consisted of the same brick clay with no additional stabiliser added and prepared to the same moisture content. All the bricks were extruded at an average moisture content of 15.6% and gave an average dry density of 1928kg/m^3. There was no significant variation in these measurements between the different tests therefore assumed to be constant in terms of the contribution to strength gain. The effect of stabiliser type, drying regime and curing time can be independently analysed.

5.1 Effect of lignosulphonate type

The effect of stabiliser type was evaluated by testing three different types of lignosulphonate. The results show that the addition of any lignosulphonate based stabiliser will not have a detrimental effect but can significantly improve the dry compressive strength of the bricks. All of the bricks, including those stabilised, that were tested under the wet regime disintegrated and therefore were not tested.

Calcium lignosulphonate was the most effective stabiliser and achieved the maximum compressive strength of 7.65 MPa when oven dried at 105°C, representing a 126% increase over the equivalent unstabilised samples. The improved performance of calcium over sodium and ammonium may be due to the process of cation exchange. The monovalent sodium cation (Na^+) is present, along with water molecules, within the double layer of certain clay minerals. Therefore cation exchange would be limited. The higher valence calcium cation (Ca^{2+}) preferentially will exchange with the cations present within the clay structure. Ammonia ions (NH_4^+) may also exchange with some of the metal cations present in clay and adhere to the negative edges of the particles. Cation exchange has the effect of a reduction in the size of the double layer, as well as leading to increased flocculation (Prusinski and Bhattacharja, 1999).

Cation exchange would be particularly prevalent with the montmorillonite fraction but limited with kaolinite. Considering the percentage weight of these minerals cation exchange of the whole sample may be dominated by kaolinite and therefore limited. Bell (1996) comments that “very small amounts of certain clay minerals may exert a large influence on the physical properties”. The alternative source of strength increase

may be due to the adhesive properties of the lignosulphonate. If only the anionic lignosulphonate is involved in the adhesion process then the strength increase would be uniform. If the cation is involved in the process then it may be reasonable to assume that varying the cation will vary the adhesion and hence compressive strength. Alternatively the cation present may cause a change in pH of the water that may lead to slightly different reactions occur that cause the variation in compressive strength.

5.2 Effect of drying regime

Testing all the samples of lignosulphonate stabilised clay, but accelerating the drying, evaluated the effect of drying regime on performance. A sample was cured within the laboratory environment and acted as a control to compare the drying regime. The compressive strength of the unstabilised sample showed a negligible increase in compressive strength. However the accelerated drying of the lignosulphonate stabilisers showed a increase in strength at 14 days but a decrease at 14 days. The increase in temperature from 60°C to 105°C resulted in an increase in compressive strength for all 14 day samples. This was most noticeable with the calcium lignosulphonate that resulted in a 24% increase in strength from the 60°C to 105°C. Increased drying temperature over the first few days resulted in a decrease of testing moisture content at 14 days. By 28 days the stabilised samples left to dry in the laboratory environment achieved a greater strength than those subject to accelerated drying. There appears to be a time dependent effect related to the effect of the initial acceleration of drying.

5.3 Effect of curing time

The effect moisture content on the strength and how this varies over time and with different drying regimes should be considered. There were marginal changes in strength for the unstabilised samples from 14 to 28 days. This suggests that these samples achieved equilibrium moisture content by 14 days. The lignosulphonate stabilised samples change in strength was dependent on the initial drying regime.

The effectiveness of lignosulphonate for increasing dry compressive strength may be related to the rate of drying. The rate of drying would increase due to an increased hydraulic gradient due to a higher surface temperature than core temperature of the brick, causing water to move through the pores at a greater rate. This movement would allow the dissolved lignosulphonate salt to move through the brick enabling cation exchange and coating of the particles with the adhesive. If this effect was accelerated then it might be expected that the 14 day strength would be greater as more lignosulphonate adhesive would precipitate out of solution. By 28 days the laboratory dried sample would have lost more moisture giving the gain in strength. The slower drying rate would have meant that the movement of the dissolved salt could happen over a greater amount of time allowing for more reactions to occur which results in strength gain. There is a significant increase in moisture content for the lignosulphonate samples dried at 105°C which would account for the general decrease in strength. The effectiveness of lignosulphonate to stabilise extruded unfired earth is potentially dependent on moisture content and therefore dependent on drying regime and curing time.

Table 2: Compressive strength and moisture content at testing

Curing regime	Age	Moisture condition at testing	Unstabilised		Na Lignosulphonate 2.5%		Ca Lignosulphonate 2.5%		Am Lignosulphonate 2.5%	
			UCS MPa	MC %	UCS MPa	MC %	UCS MPa	MC %	UCS MPa	MC %
Lab Dry	14 Days	Dry	3.17	2.23	3.08	3.19	4.11	3.09	4.62	2.89
	28 Days	Dry	3.24	1.84	6.01	1.67	7.23	2.05	7.00	1.84
Oven - 60	14 Days	Dry	3.19	1.27	5.21	1.46	6.19	1.61	6.00	1.10
	28 Days	Dry	3.33	1.35	4.34	1.36	6.69	1.67	6.57	1.22
Oven - 105	14 Days	Dry	3.39	1.44	5.59	1.14	7.65	1.11	6.07	0.69
	28 Days	Dry	3.39	1.42	4.38	1.28	6.47	1.42	6.01	1.35

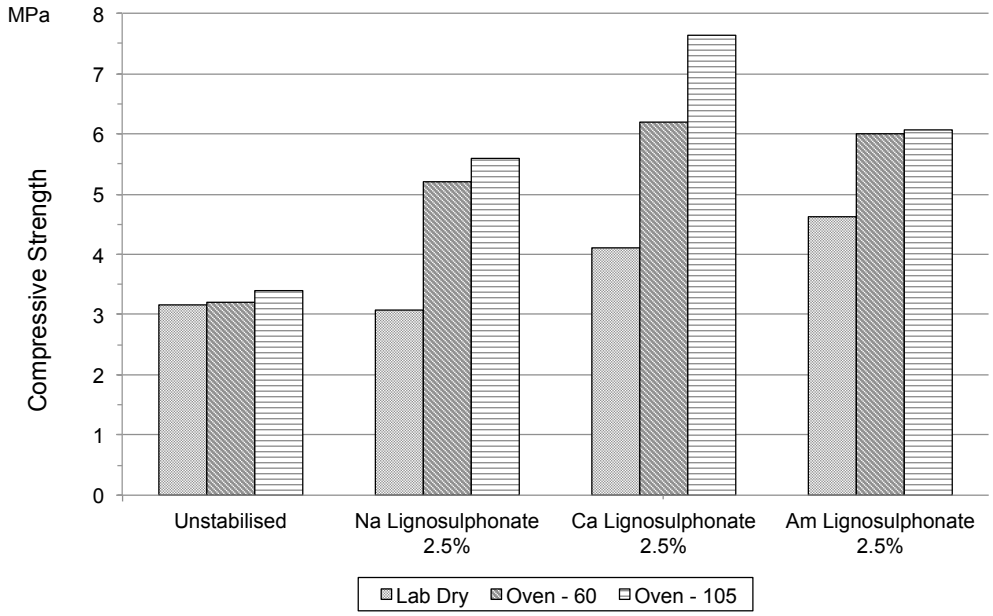

Fig. 3: 14 day compressive strengths

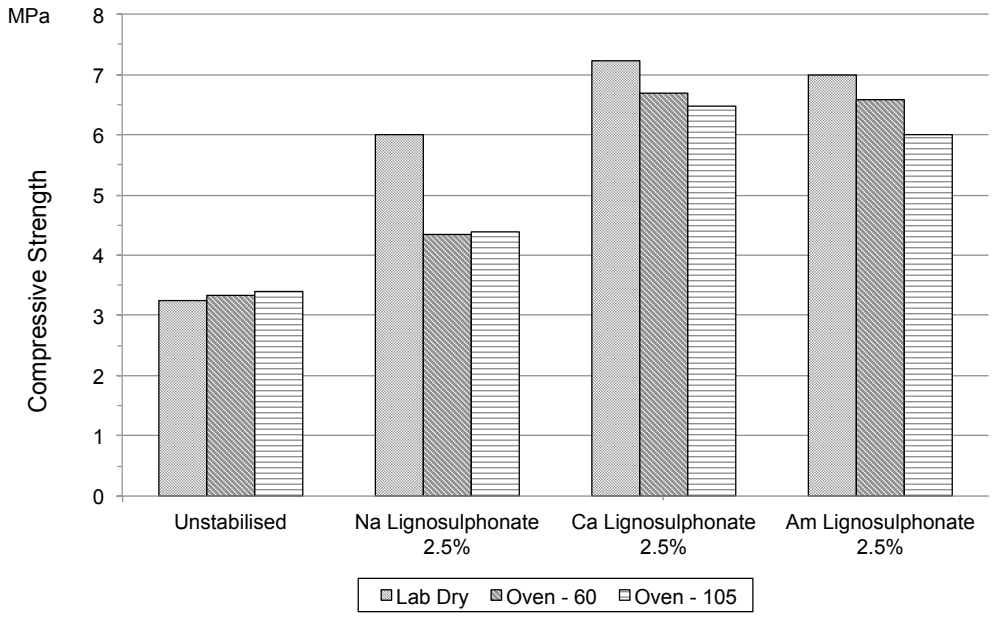

Fig. 4: 28 day compressive strengths

6 SUMMARY AND CONCLUSIONS

Although the exact type of lignosulphonate varies, it has shown that lignosulphonate will not have a detrimental effect on the compressive strength and in most cases leads to significant dry strength increase when compared to unstabilised samples. Maximum strength increase was achieved with calcium lignosulphonate that was dried for two days at 105°C and tested at 14 days. The greatest improvement of strength at 28 days was achieved when the curing period did not involve elevated temperatures. There is clearly scope for further research to optimise the drying regime to possible achieve further strength gains. In addition, there is scope for further research into optimum stabiliser quantity. Considering the mechanisms involved it is likely that calcium lignosulphonate will remain the stabiliser that gives the greatest strength improvement. The long term performance of lignosulphonate stabilised earth and the relationship to moisture content remains unknown and should be investigated.

All of the bricks that were fully immersed in water were unable to be tested as they had been completely disintegrated. An increase in concentration of stabiliser may provide enough adhesion, however solubility of the material remains a concern. The method of testing by full immersion could be considered to harsh and was the conclusion of Tingle and Santoni (2003). As saturated performance of earth masonry remains one of the greatest barriers to commercial adoption then it will be required to meet this testing method.

This work has show than there is significant potential for strength increased with lignosulphonate. Lignosulphonate was shown to be ineffective at stabilising against elevated moisture contents. Earthen bricks are targeted towards for the domestic application where an increase in strength is not required compared to moisture resilience. Therefore stabilising earth masonry with lignosulphonate has been shown to be ineffective.

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